

COMPARISON OF COMPOSITE BEAM-COLUMN CONNECTION DEVELOPMENT UNDER CYCLIC LOADING USING FINITE ELEMENT MODELLING

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Abstract

Composite beam-column connection offers several advantages compared to conventional concrete beam-column connection. As instance, high load-bearing capacity, good serviceability, high stiffness, drift capacity, minimized energy displacement, practical fabrication, high efficiency, high deformation capacity, high durability, and cost-effectiveness, as well as a reduction in structural loads and element dimensions. In high-seismic areas, the use of composite steel-reinforced concrete (SRC) structures has been observed to exhibit ductile behaviour. This research investigates several aspects of the criteria required for the structural elements of composite beam-column connections integrated with WF and H-beam profiles. That study compares five beam-column joint models consisting of RC and four SRC developments use the Finite Element Method with the ABAQUS program to obtain the behaviour under cyclic loading. Based on several obtained results and parameters, it can be concluded that All models showed failure in the beam elements, confirming the strong column-weak beam principle. Composite SRC beam-column joints produced higher moments than the RC model, but SRC models experienced less beam rotation. SRC-01 was identified as the most ideal model with superior structural performance in resisting seismic forces.

Keywords:

Composite materials;
 Beam column connection;
 Cyclic loading;
 Seismic behavior;
 Steel reinforced concrete.

1 Introduction

The moment-resisting frame system in the beam-column connection element is designed to be rigid; the behavior under seismic loads is often disregarded, and modifications to the beam-column connections for buildings located in high seismic risk areas are needed to enhance the structure's ability to adapt to changes in environmental [1]. The beam-column connection element is the most critical member in building structures. Therefore, beam-column connections must be properly detailed to transfer complex forces in the joint area [2][3][4]. Various types of beam-column connections have been developed; one of these is the composite beam-column connection. Numerous studies on the structural behavior of composite beam-column connections have shown that the connection structure exhibits different behavior compared to conventional beam-column connections [5]. e Composite beam-column connections, such as the Reinforced Concrete Steel Frame, which involves combining concrete columns and steel beams, is a type of connection that offers several advantages compared to conventional concrete beam-column connections or steel column connections. Some of these advantages include high load-bearing capacity, good serviceability, high stiffness, drift capacity, minimized energy displacement, practical fabrication, high efficiency, high deformation capacity, high durability, and cost-effectiveness, as well as a reduction in structural loads and element dimensions [6][7][8][9][10][11][12][13][14][15][16]. Composite column structures are classified into two types, namely concrete encased steel (CES), commonly known as steel wrapped in concrete, and concrete-filled steel tube (CFST), commonly known as steel wrapped in a concrete tube. Illustrations of several types of composite columns are shown in Figure 1.

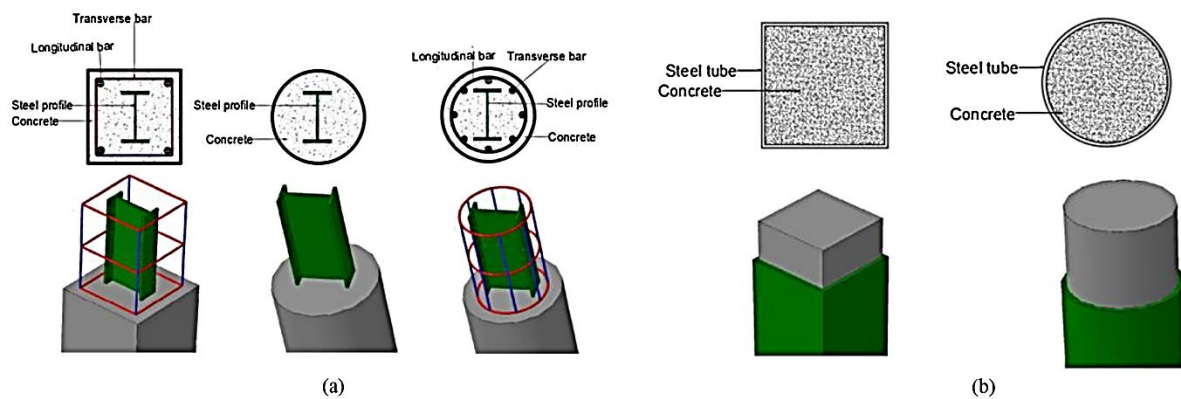


Fig. 1: (a) CES, (b) CFST [5]

Sermet et al [5] conducted research on the composite beam-column connection elements with the Concrete Encased Steel (CES) type. In that study, columns and beams are designed as WF (wide flange) sections wrapped in concrete according to the Eurocode 4 requirements. The four variations of the beam-column connection designs are illustrated in Figure 2. The analysis results indicate that the failure is determined by the beam behavior, and the connection capacity depends on the shear capacity of the beam. Meanwhile, research conducted by Le et al.[6] on a similar topic involved designing beam-column connection elements as concrete-encased steel, but with beams designed as pure steel. That study demonstrates performance under cyclic loading that meets minimum loading capacity, minimum story drift capacity, energy dissipation, and stiffness degradation, with evaluated results showing satisfactory outcomes. Modifications to the composite beam-column connection with the CFST type were carried out by Shehab and Ekmekyapar [17] by adopting a steel tube column shape. The behavior of the connection model indicates that the beam-column connection meets the criteria of a strong column-weak beam, with the continuity contribution to initial stiffness being more dominant. Two models of beam-column connection elements by Sermet et al. and Le et al. which are compared in this study, are shown in Figure 3.

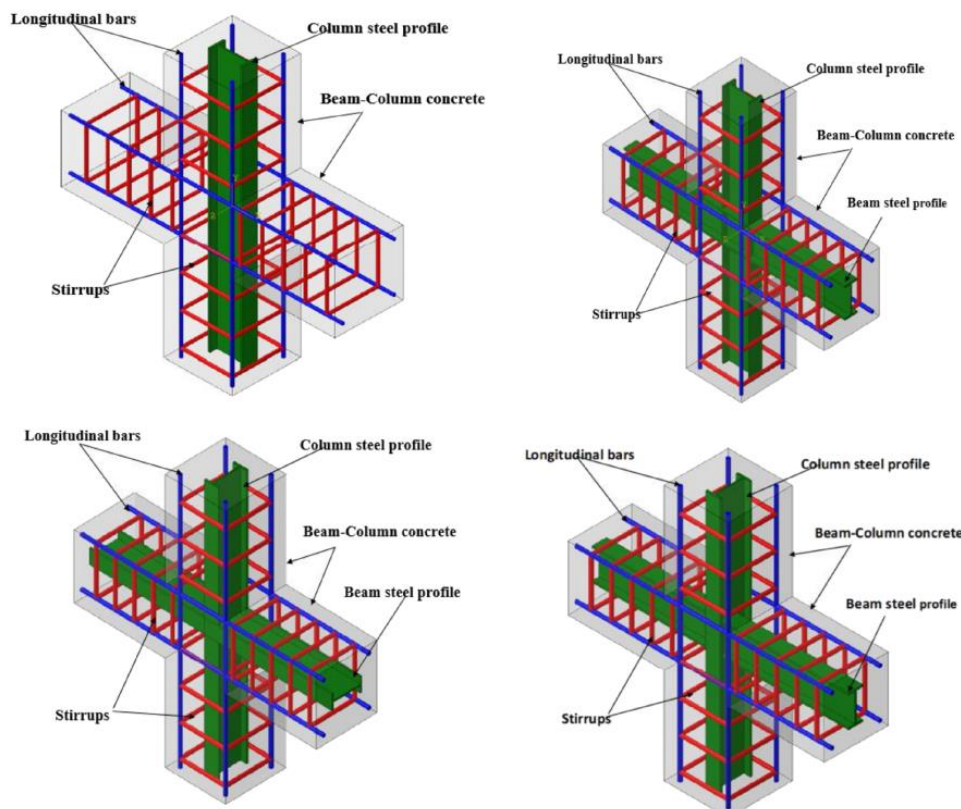


Fig. 2: Variations of the SRC beam column joint specimens by Sermet, et al [5]

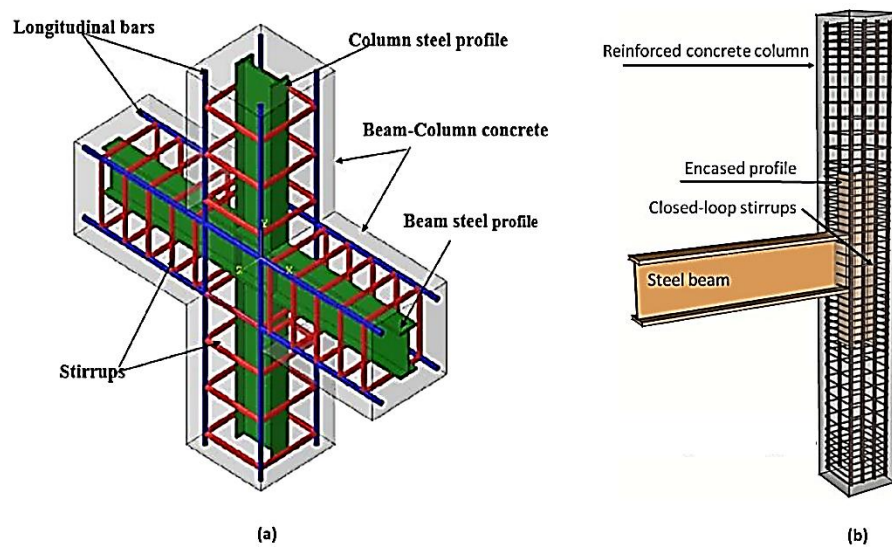


Fig. 3: Developments of composite beam-column connections by (a) Sermet, et al. (b) Le, et al. [5][6]

According to Sermet et al. [18], conventional beam-column connections exhibit complex behavior involving a combination of flexural, shear, and axial forces. As the complexity of connection elements increases, the complexity of their behavior also rises. The usage of composite beam-column connections produces complex behavior since each component in the connection has diverse material qualities and features, despite studies specifying the behavior of each element (beam and column). In high seismic areas, the use of composite steel-reinforced concrete (SRC) structures has been observed to exhibit ductile behavior, [19] developed the concept of SRC and CFT, and a new engineering solution known as wood-encased concrete-steel (EWECS) was specifically developed for regions with low to high seismic activity. This innovative composite material overcomes the limitations on the number of floors that can be constructed using wood alone. The results of this research show a hybrid structure that combines the benefits of concrete, steel, and wood to enhance structural performance in seismic regions.

Composite beam-column connections are particularly applied in precast structures because the selection of the connection type, design, and appropriate materials plays a crucial role in the performance of precast structures [20]. The critical aspect of building construction lies in the seismic behavior of beam and column connections. Numerous studies have focused on the seismic behavior of these connections, testing various configurations within different structural frameworks [21][22]. In general, a strong connection subjected to seismic loads is expected to withstand significant forces without losing its strength during elastic deformation [23]. Current earthquake design processes include characteristics that can obtain a ductile response. Columns are intended to be flexurally stronger than beams, but under extreme loads, failure tends to occur in the beam element [24]. In studies [9] and [14] regarding composite beam-column connections, elements are designed according to the specifications of the strong column-weak beam standard. The steel frame and the beam-column connection components function effectively as force transmission components between beams and columns. The application of SRC connections can increase stiffness, as evidenced by the research [5], where the use of SRC connections concluded that the stiffness degradation in the control specimen (RC) experienced a decrease in stiffness of 29.91%, while in SRC connections it experienced a decrease in stiffness of 26.90%. Therefore, the application of SRC to beam-column connection elements can reduce strength degradation. This is also proven in the research [22], where the application of composite beam-column connections concluded that composite beam-column connections can increase the maximum drift ratio by up to 9.5%, whereas monolithic connections only achieved a drift ratio of 5%.

Several models of composite beam-column connections were continuously developed to meet the requirements of strong and ductile connection elements to be applied as earthquake-resistant elements. The planned structural elements designed to withstand cyclic loads must meet the detailing requirements for earthquake-resistant structural elements. To achieve this goal, the design of a hierarchy of failures is needed, ensuring that only ductile failure modes emerge. Flexural failure is an

example of a ductile failure mode, while shear failure is generally prone to breaking. To achieve ductile failure, structural elements are typically designed with a higher flexural strength than the maximum shear force. The failure point must be designed in the intended position so that undesirable components collapse prominently. This theory should be applied to the design and modeling of beam-column connection elements. In this research design, the investigation was conducted regarding several aspects of the requirements that are necessary for the structural elements of composite beam-column connections integrated with WF profiles and H-beam profiles. It is expected that the developed model can be categorized as a reliable and strong element for resisting seismic loads. This research develops connection details using structural steel components for moment-resisting connections between beams and columns. Numerical analysis of beam-column connection elements under cyclic loads was conducted to determine the connection's performance under cyclic loading. Analysis of the modeling was performed by the ABAQUS program.

2 Novelty and Significance

Based on the research background, there is a need for a composite beam-column connection element structure to facilitate assembly and earthquake resistance, making it applicable in Indonesia, which is a high seismic zone. It is expected that the developed model can be categorized as a reliable and strong element for resisting seismic loads. This research compares two connection details developed using structural steel components beam-column connection elements between Sernet et al. and Le, et al. Research. The research development carried out was also compared to the effect of shear reinforcement in the plastic hinge area. The study was conducted analysis using the numerical Finite Element Method (FEM) with the ABAQUS program to understand the detailed behavior, especially when the structure is subjected to cyclic loading. The Finite Element Method (FEM) is a numerical solution method for equations that address problems represented in differential or integral form [25]. The model to be examined is interior beam-column connections. Research parameters for behavior include failure patterns, the hysteresis curve, and energy dissipation.

3 Materials and Methods

In performing numerical simulations of beam-column connections, the FEM-based software ABAQUS/CAE was chosen. This analysis software can solve both elastic and inelastic problems of static or dynamic responses of model. To model in inelastic conditions, an analysis of the plastic conditions of each material is required. In this study, the CDP model was proposed by Birtel and Mark [26]. The CDP model by Birtel and Mark is used because studies utilizing the ABAQUS program have referred to that model. Meanwhile, the steel material refers to Jia and Kuwamura [27] research with steel grade SS400. In this study, that model was chosen because the steel material grade in the research by Jia and Kuwamura is similar to the steel grade used in this research.

3.1 Material Modelling of Concrete

The Concrete Damage Plasticity model was selected due to its ability and suitability for simulating reinforced concrete in different structural forms. The CDP can determine the nonlinear behavior of beam-column connections. In this research, the concrete strength is planned at 30 MPa. Additionally, this model accounts for the concept of isotropic damage elasticity with isotropic compressive and tensile plasticity. CDP also considers the degradation of elastic stiffness caused by plastic strains in both compressive and tensile conditions. The CDP model illustrates the damage to a material, with the primary failure modes being tensile cracking and compressive crushing [28]. The CDP model requires the following material functions:

- Stress-strain relationships for uniaxial behaviour under compressive and tensile loads, including cyclic loading.
- Functions for the damage variables d_c and d_t under loading.

The stress-strain behaviour under sustained compressive loads is modelled in three phases, as shown in Figure 4.

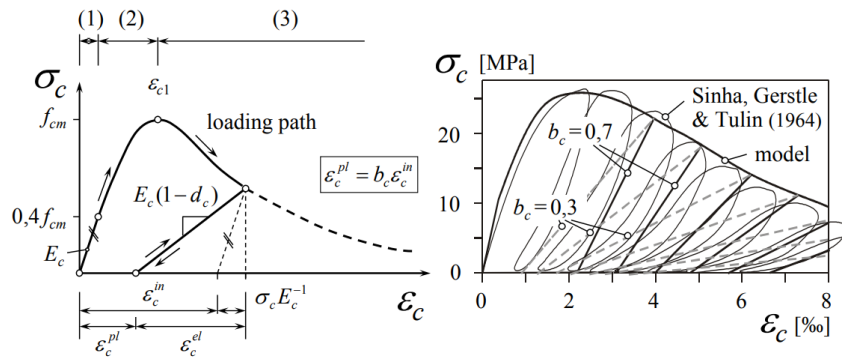


Fig. 4: Stress-Strain Relationship under Cyclic Load [26]

The compressive damage component dc is shown in equation (1) in relation to the corresponding plastic strain, where the condition of inelastic strain is determined using the factor b_c with $0 < b_c \leq 1$.

$$dc = 1 - \frac{\sigma_c E_c^{-1}}{\epsilon_c^{pl} \left(\frac{1}{b_c} - 1 \right) + \sigma_c E_c^{-1}} \quad (1)$$

where:

dc = compressive damage
 σ_c = compressive strength
 ϵ_c^{pl} = plastic strain
 E_c = modulus elasticity
 b_c = 0,7

Similar to Equation 1, the damage dt depends on an experimentally determined parameter $b_t=0.1$. Therefore, the load is assumed to return almost to the initial point, leaving only a small strain. The equation related to tensile failure is shown in Equation 2.

$$dt = 1 - \frac{\sigma_t E_c^{-1}}{\epsilon_t^{pl} \left(\frac{1}{b_t} - 1 \right) + \sigma_t E_c^{-1}} \quad (2)$$

where:

dt = tensile damage
 σ_t = tensile strength
 ϵ_t^{pl} = plastic strain
 E_c = modulus elasticity
 b_t = 0,1

3.2 Material Modelling of Steel

Modelling the plasticity of steel materials is crucial in the analysis of steel structures subjected to cyclic loads. Various plasticity models have been proposed over the past decades, and a comprehensive review of the field can be found in the research Jia and Kuwamura [27]. In general, to explain the plasticity behaviour of metals, it is necessary to provide:

- A yield function that determines the yield condition.
- A flow rule that defines the plastic strain equations.
- A hardening rule that determines the behaviour after yielding.

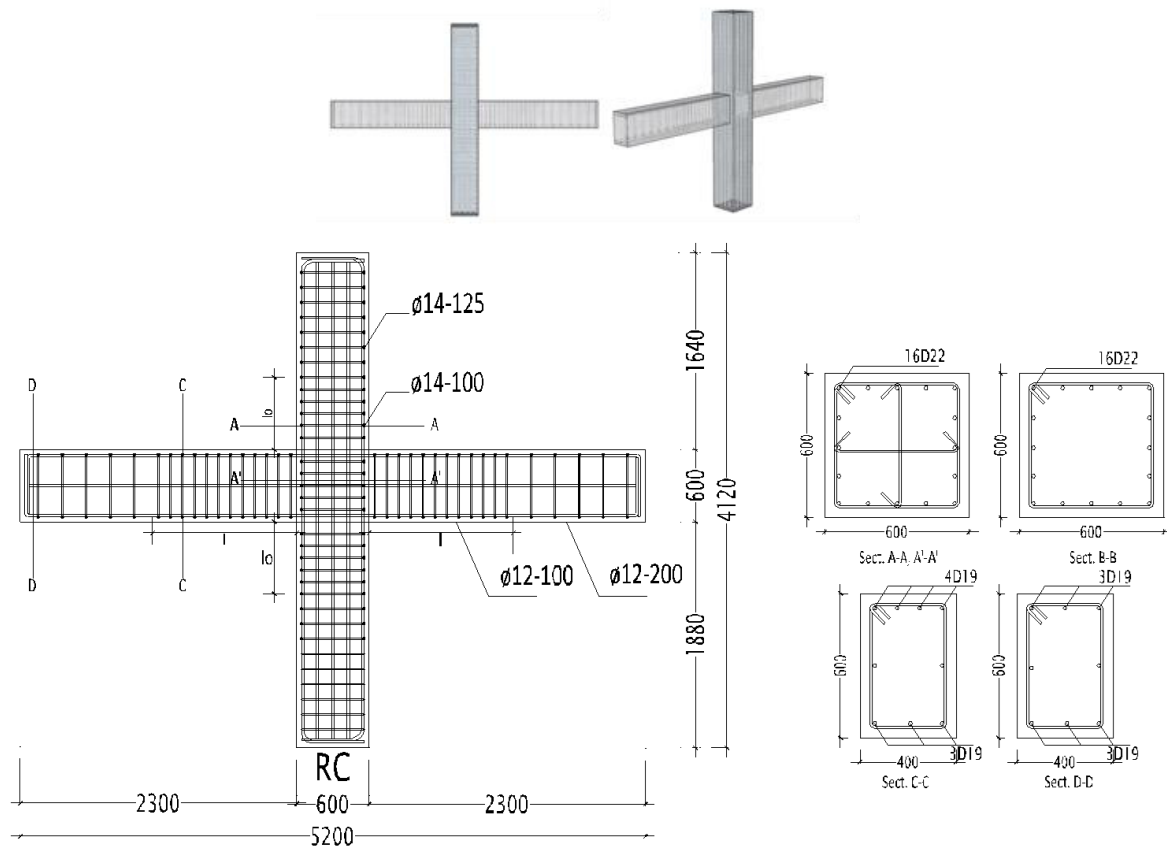
In the study [27], a comparison was made between the Chaboche model and the Yoshida-Uemori model, concluding that the modified Chaboche model provides better simulations than the Yoshida-Uemori model. Several parameters related to the plasticity model for steel materials (Chaboche model) are shown in Table 1. These parameters are incorporated into the ABAQUS modelling of steel materials for the composite beam-column connection model.

Table 1: Material Parameters of Plasticity Model [27]

Parameter	Without Isotropic Hardening	With Isotropic Hardening
σ_{y0}	255.9	255.9
C_1	97.2	26.9
C_2	97.2	1617.2
C_3	3,763.0	26.9
γ_1	0	0
γ_2	0	10.7
γ_3	13.7	0
k	-	5.7
Q_{∞}	-	227.8

3.3 Details of Connection and Geometry of The Models

In this study, a comparison was made between two different composite connection models/types, namely the model developed by study [5] and study [6]. In study [5], research was conducted on Concrete-Encased Steel (CES) with WF and H-Beam profiles, and both longitudinal and shear reinforcement were applied to the connection development model. However, in this study, modifications were made to the development model [5], with and without shear reinforcement in the CES area. Meanwhile, the connection type developed the study [6] also applied CES, but modifications were made to the beam, which is purely steel with the beam ends welded to the steel profile embedded in concrete. The capacity of the conventional beam-column connection (RC) as a control model in the study was designed according to [29]. The connection details are shown in Figure 5(a)-(e) and Table 2.



(a)



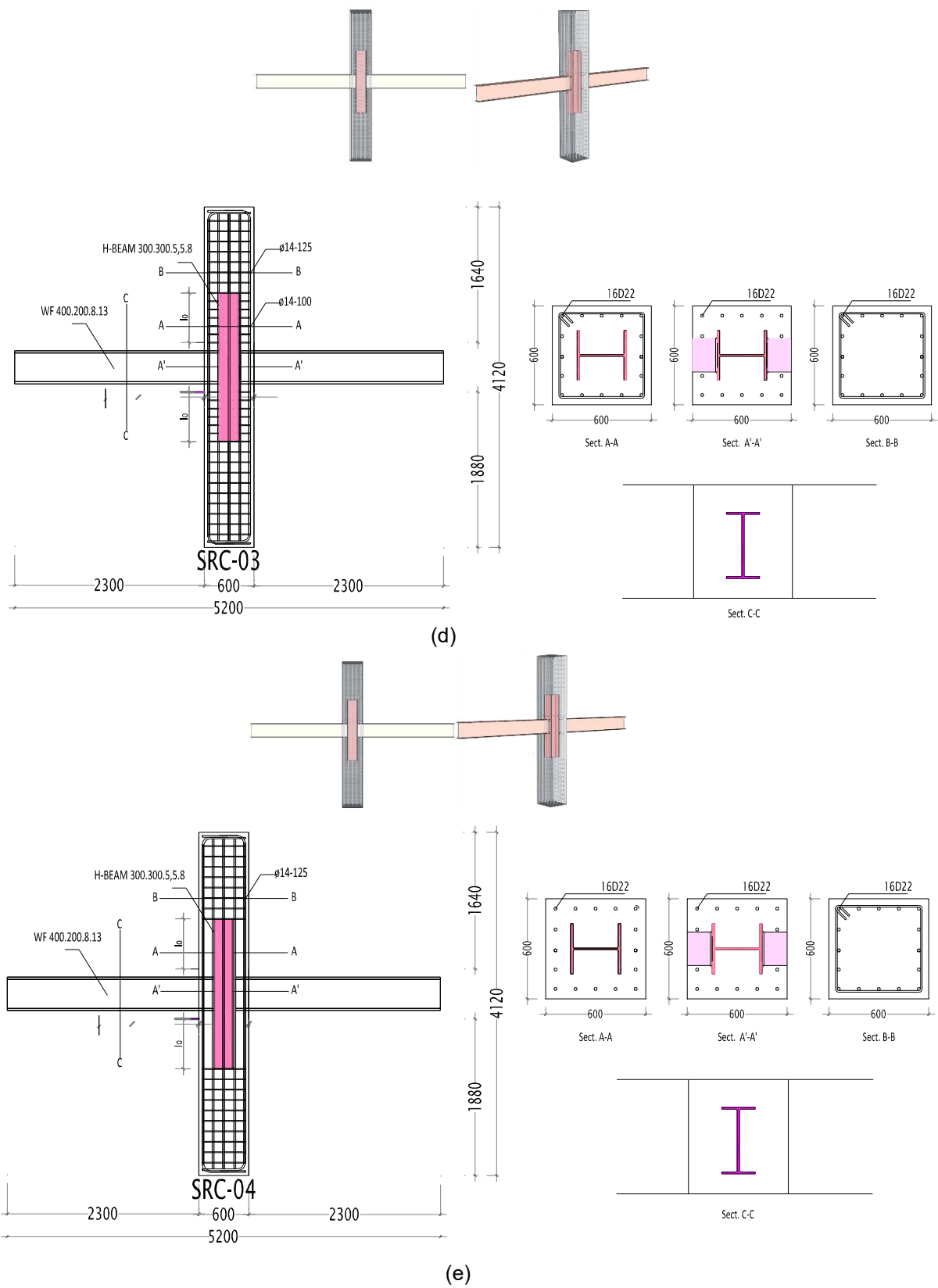


Fig. 5: Steel Reinforced Concrete Beam Column Connection (a) RC (b) SRC-01 (c) SRC-02 (d) SRC-03 (e) SRC-04

Table 2: Research parameters and properties of the models.

Model	Research Parameter	Material Properties	Reinforcement Detail	
			Column	Beam
RC	Monolithic	Concrete f_c 30 Mpa Steel Reinforcement Stirrup f_y 280 Mpa, f_u 405 MPa Flexural f_y 420 Mpa, f_u 525 MPa	Flexural : 16D22 Stirrup : $\varnothing$ 14-100 $\varnothing$ 14-125	Flexural : 7D19 Stirrup : $\varnothing$ 12-100 $\varnothing$ 12-200
SRC-01	Concrete-Encased Steel in Column and Beam	Concrete f_c 30 Mpa Steel Reinforcement Stirrup f_y 280 Mpa, f_u 405 MPa Flexural f_y 420 Mpa, f_u 525 MPa Steel Profile f_y 255 MPa, f_u 510 MPa	Flexural : 16D22 Stirrup : $\varnothing$ 14-100 $\varnothing$ 14-125	Flexural : 7D19 Stirrup : $\varnothing$ 12-100 $\varnothing$ 12-200
SRC-02	Concrete-Encased Steel in Column and Beam without stirrup in Plastic Hinges Area		Flexural : 16D22 Stirrup : $\varnothing$ 14-200	Flexural : 7D19 Stirrup : $\varnothing$ 12-200
SRC-03	Concrete-Encased Steel in Column and Steel Beam		Flexural : 16D22 Stirrup : $\varnothing$ 14-100 $\varnothing$ 14-200	-
SRC-04	Concrete-Encased Steel in Column and Steel Beam without stirrup in Plastic Hinges Area		Flexural : 16D22 Stirrup : $\varnothing$ 14-200	-

3.4 Loading Configuration and Boundary Condition

In this study, the interior beam column connection was analyzed under cyclic loading, following the loading protocol referred to in [30] (Figure 7), with a minimum drift ratio of 4%. Figure 6 depicts the loading configuration with related supports. The loading history is determined by two factors, which include:

1. Improved deformation control configurations for specifying different levels of deformation.
2. The number of cycles at each deformation level.

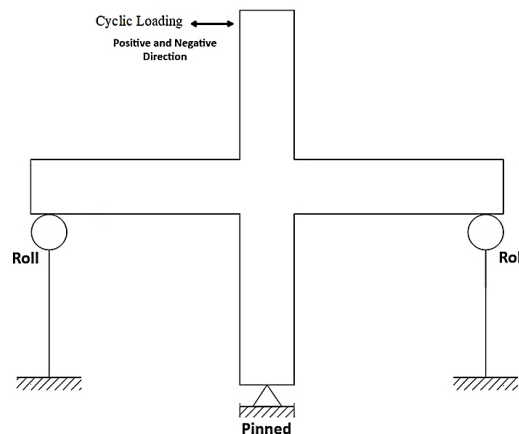


Fig. 6: Loading Scheme

Based on [30], in the cyclic loading procedure, a minimum of two cycles is applied at each displacement level. In this study, three cycles were applied at each displacement level to ensure the occurrence of stable structural failure [31]. The drift ratio (6%) was calculated based on the effective height of the column.

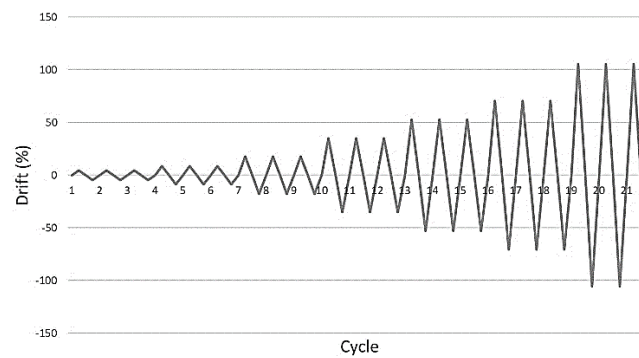


Fig. 7: Cyclic Loading Procedure [30]

3.5 Seismic Performance Parameters of Beam-Column Connection Elements

After performing the modeling using the ABAQUS program, the performance results of the proposed connection were obtained to compare the control model (RC) with the SRC model (SRC01-SRC04). Some of the comparisons included the load-drift ratio relationship, energy dissipation, and the moment-rotation relationship, leading to conclusions from several research parameters.

a. Load-Drift Ratio

Structural testing under cyclic loads can be observed through the hysteresis curve between lateral load and lateral displacement, where cyclic loading refers to repeated loading. The primary cause of failure is due to fatigue failure, where concrete is in a cracked condition as repetitive failure occurs [32].

b. Energy Dissipation

Inelastic deformation in the beam-column joint supports sufficient energy absorption through hysteretic behavior, thus reducing energy transmission and ensuring that the structural performance under earthquakes meets the requirements. Energy dissipation and the equivalent viscous damping ratio are important indicators, calculated based on the hysteresis loop. Cumulative energy dissipation is evaluated as the energy dissipation from the level of the drift ratio. The depiction of the equivalent viscous damping ratio can be seen in Figure 8, where $S(ABC + CDA)$ represents the total area of both the right sides of triangles OBE and ODF [31].

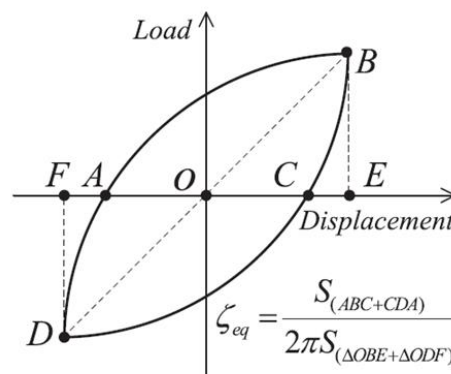


Fig. 8: The calculation theory of Energy Dissipation Capacity in the specimen [31].

c. Moment-Rotation

Column rotation occurs due to four primary mechanisms: elastic bending of the beam, relative slip of the longitudinal bars in the core area, plastic hinge formation at the beam ends, and bending of the column. The design concept of "strong column and weak beam, strong connection and weak member" is generally applied in structural planning, leading to the conclusion that shear deformations in the core zone contributing to relative rotation are considered insignificant [33]. Rotation refers to the angle formed between the tangent line at the deflected shape of a structure and its original axis, expressed in degrees or radians. In this study, the moment-rotation relationship is examined in the formation of plastic hinges at the beam ends at the face of the column.

4 Result and Discussion

In this study, a comparison of structural performance under cyclic loading is conducted using numerical analysis with the finite element method through computer simulation with the aid of ABAQUS/CAE 2022. The discussion of results for the beam-column connection elements includes Stress Distribution, Lateral load-drift ratio relationships, Energy dissipation capacity, and Moment–rotation relationships. The modelling with ABAQUS is shown in Figure 9. The mesh application is done per part with a mesh size of 100 mm. The iteration technique in the ABAQUS program uses Full Newton with 8 numbers of iterations allowed before the kernel matrix is reformed. The interaction of steel within the concrete uses the Embedded function.

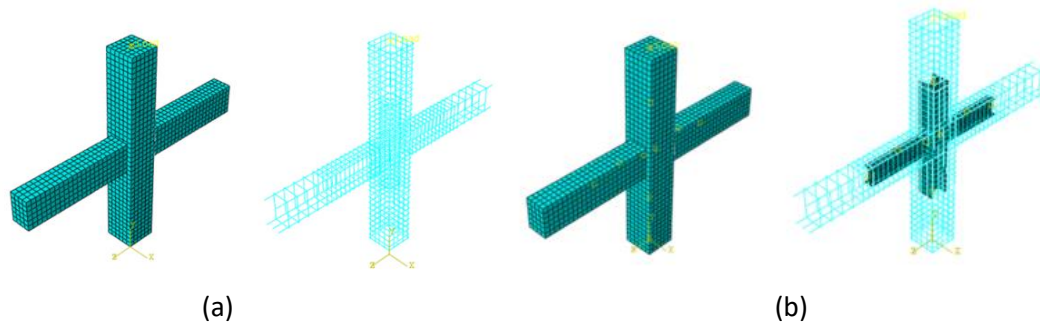
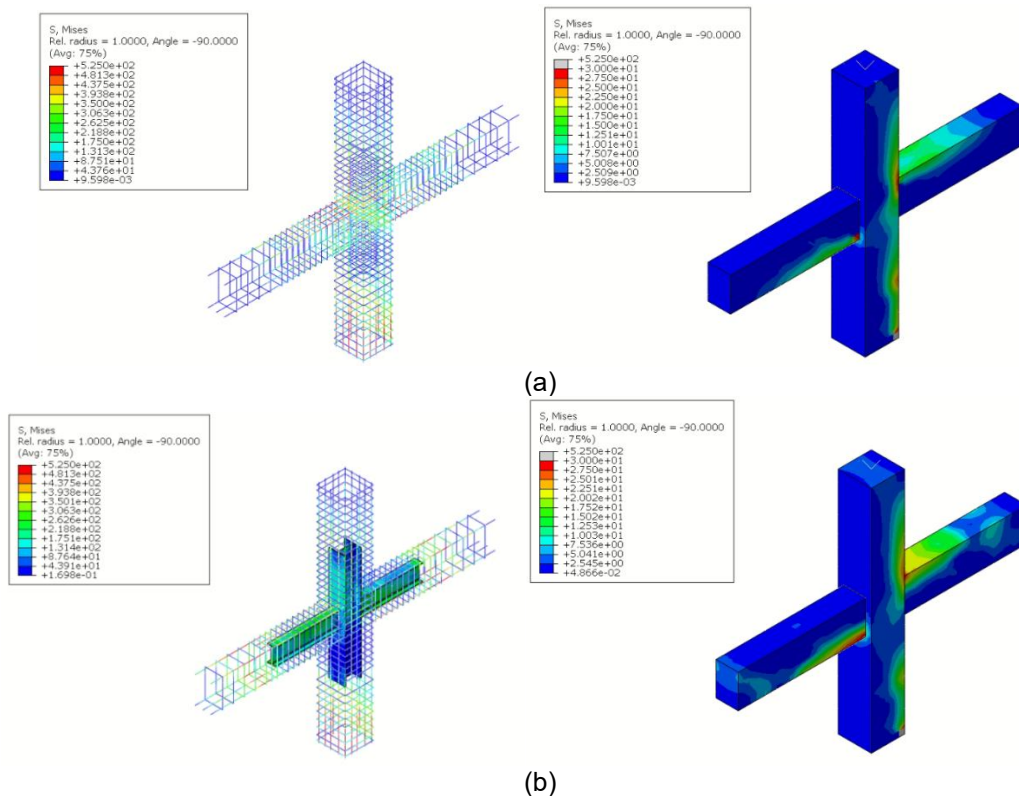


Fig. 9: Solid Element and Embedded Steel for the Beam-Column Connection in ABAQUS : (a). RC (b). SRC-01

4.1 Stress Distribution

The stress distribution of five beam-column connection models using ABAQUS is shown in Figure 10. The maximum stress at an 8% drift ratio occurs in the beam element at the face of the column. The failure mode in each developed SRC model is similar to the control model (RC), indicating that failure occurs in the beam rather than the column and joint area. Therefore, it can be concluded that the failure mode follows the strong column weak beam principle. In the SRC-01 and SRC-02 models, maximum stress occurs in the steel reinforcement just outside the SRC beam element area, indicating that the SRC significantly influences the failure pattern. For the SRC-03 and SRC-04 models, stress occurs in the steel beam element at the face of the steel column.



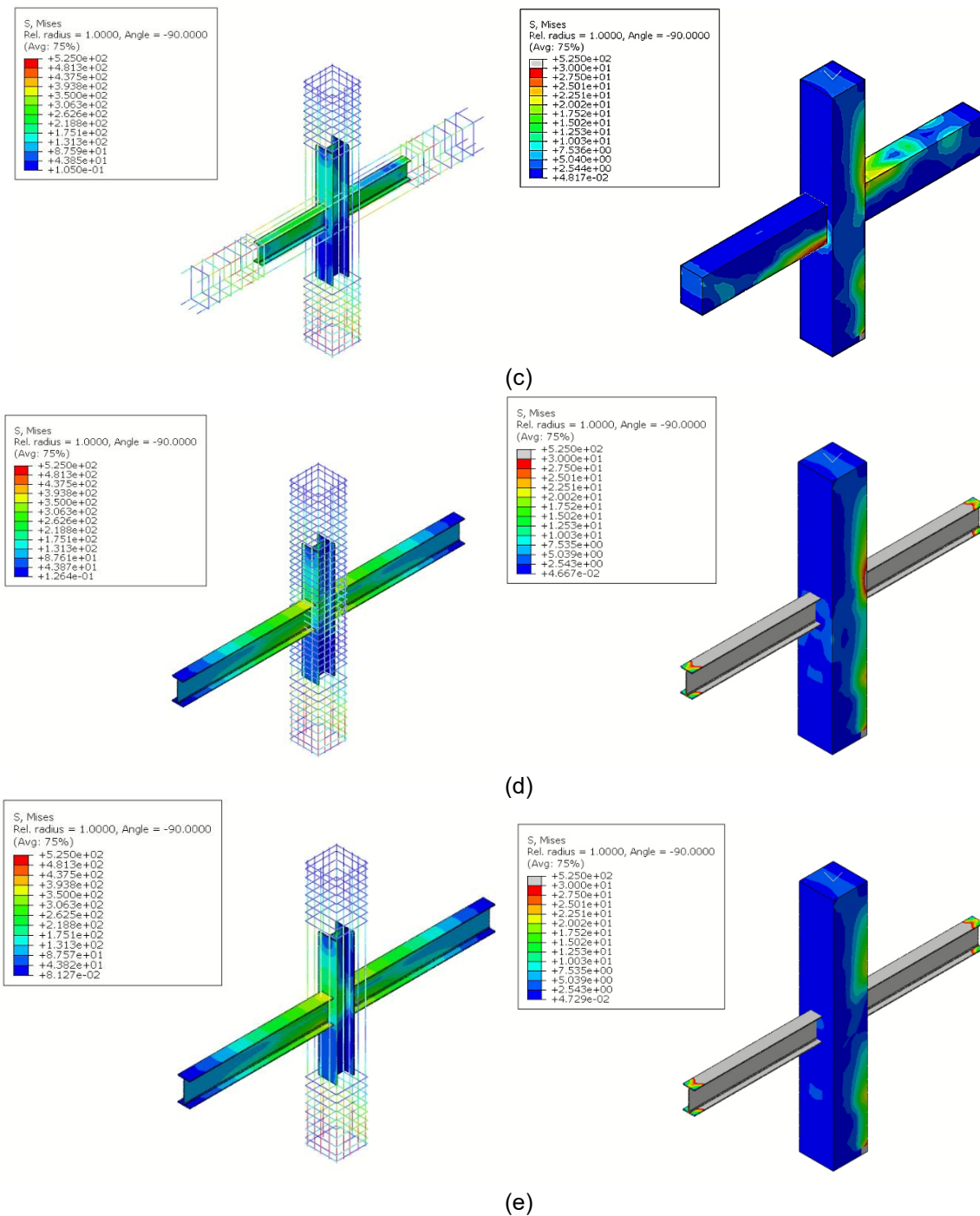


Fig. 10: Stress Distribution of the numerical models : (a) RC, (b) SRC-01, (c) SRC-02, (d) SRC-03, (e) SRC-04

4.2 Lateral Load-Drift Ratio Relationships

The lateral load-drift ratio curve is shown in Figure 11 and the Backbone Curve is shown in Figure 12. Several results related to the load-drift ratio relationship are presented in Table 3, where the first yield occurs at a drift ratio of approximately 1%. Since the modelling was conducted with a target maximum displacement of only up to 6%, $P_{ultimate}$ has not been obtained, and thus, the ductility value cannot be analyzed. The yield condition of each specimen occurred at a 1% drift ratio, with the largest yield force (P_y) reaching 478.93 kN in the negative direction for specimen SRC-01, while the lowest P_y occurred for specimen SRC-03 with a value of 298.48 kN in the negative direction.

Table 3: Numerical Result of The Models

Model	Load Direction	Δy [%]	P_y [kN]	P max [kN]	P max/P max RC [%]	Avg [%]
RC	Positive	0.999%	361	393.00	100%	100%
	Negative	-0.994%	-362	-395.16	100%	
SRC-01	Positive	0.959%	461.77	490.78	125%	127%
	Negative	-0.995%	-478.93	-510.43	129%	
SRC-02	Positive	0.988%	461.27	486.90	124%	126%
	Negative	-0.999%	-476.49	-507.84	129%	
SRC-03	Positive	0.981%	302.19	462.82	118%	118%
	Negative	-0.958%	-298.48	-468.49	119%	
SRC-04	Positive	0.980%	300.21	459.22	117%	117%
	Negative	-0.973%	-301.87	-464.60	118%	

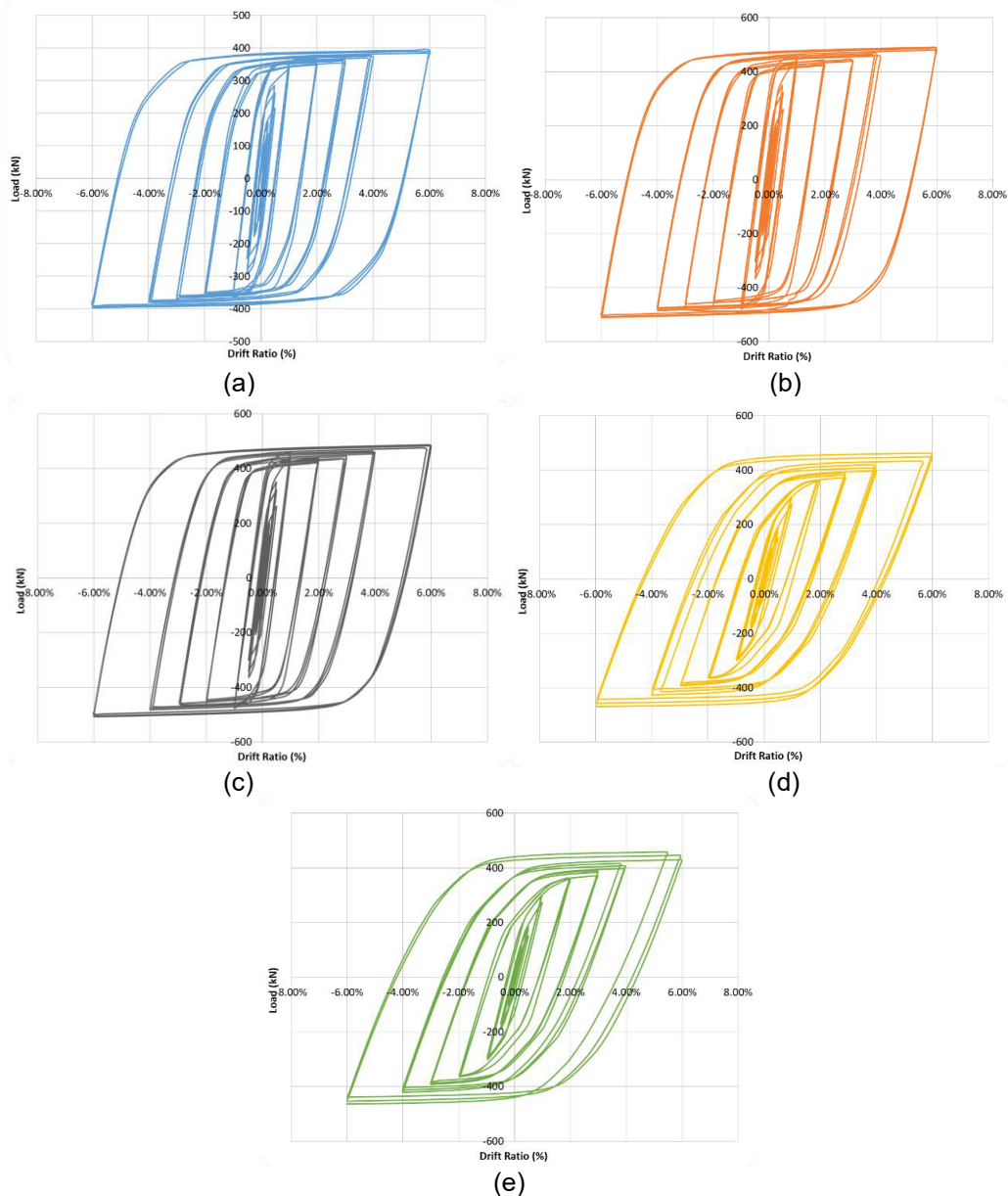


Fig. 11: Hysteresis Curve Load-Drift Ratio of the models : (a) RC, (b) SRC-01, (c) SRC-02, (d) SRC-03, (e) SRC-04

Based on the hysteresis curve results, it was found that the SRC-01 model has the highest capacity compared to the other models. The modified SRC models have a greater capacity compared to the

control model (RC). Specifically, the SRC-01 and SRC-02 models have capacities that are 27% and 26% greater than the RC model, respectively, while the SRC-03 and SRC-04 models have capacities that are 18% and 17% greater than the RC model. This indicates that the SRC plays a significant role in the capacity of the beam-column connection elements. Comparisons between the SRC-01 – SRC-02 models and the SRC-03 – SRC-04 models show that the use of shear reinforcement in the SRC area of the beam element does not have a significant impact, as the capacities and behaviours are not vastly different. The SRC-01 capacity is only 0.5% greater than the SRC-02, while the SRC-03 capacity is 0.8% greater than the SRC-04. It can be concluded that the use of SRC in beam-column connection elements can increase shear capacity. The research results show that at a drift ratio of 6%, the ultimate condition has not yet occurred. Therefore, it can be concluded that the beam-column joint element meets the criteria as an earthquake-resistant beam-column joint element, where the minimum drift ratio refers to ACI 374.2R-2013, which is 4%.

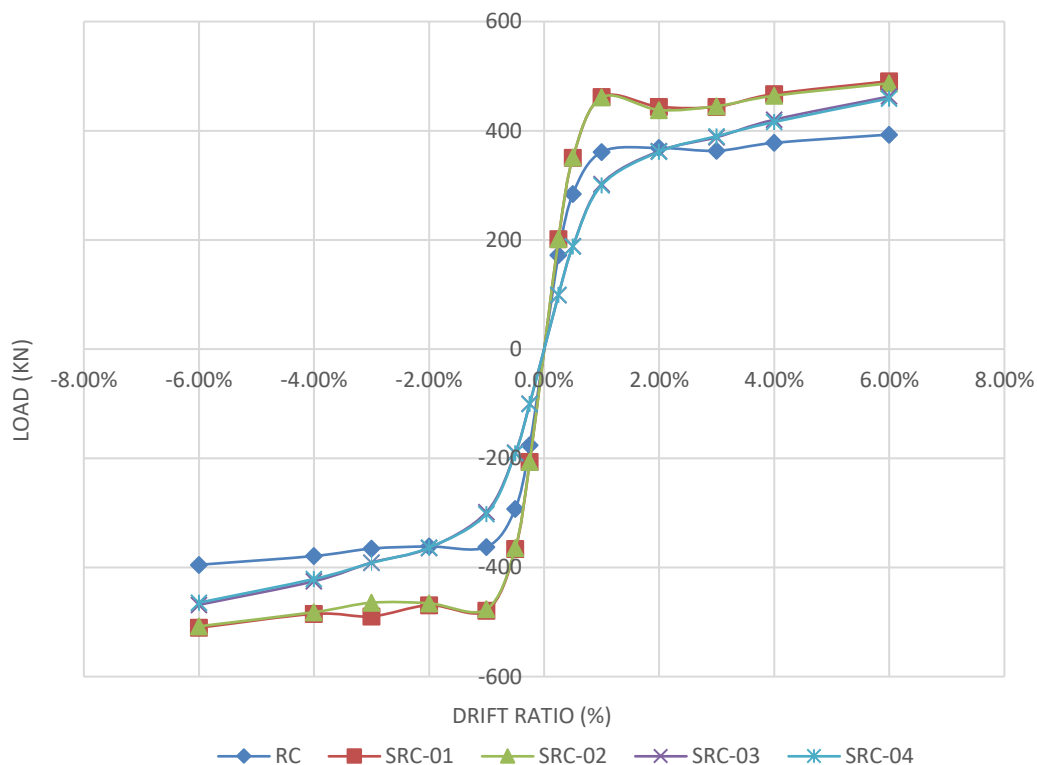


Fig. 12: Backbone Curve

4.3 Energy Dissipation Capacity

The energy dissipation in each model was analyzed using computer simulations with ABAQUS and compared among all models. The cumulative energy dissipation is presented in Figure 13. Based on the results of the modelling, it was found that the SRC-01 model has the highest energy dissipation capacity compared to the other models, while the SRC-04 model has the lowest energy dissipation capacity. The comparison between the SRC-01 and SRC-02 models and the SRC-03 and SRC-04 models, which have differences in the stirrup/shear reinforcement parameters in the joint area and plastic hinges, shows no significant difference. It can be concluded that the use of stirrups in the SRC area does not have a major impact. The energy dissipation capacity of SRC-01 is 1% higher than SRC-02, while SRC-03 is 2% higher than SRC-04. Compared to the monolithic joint, the SRC-01 model has 25% higher energy dissipation capacity, SRC-02 has 23% higher capacity, and SRC-03 and SRC-04 have 17% and 19% lower energy dissipation capacities compared to the monolithic joint (RC).

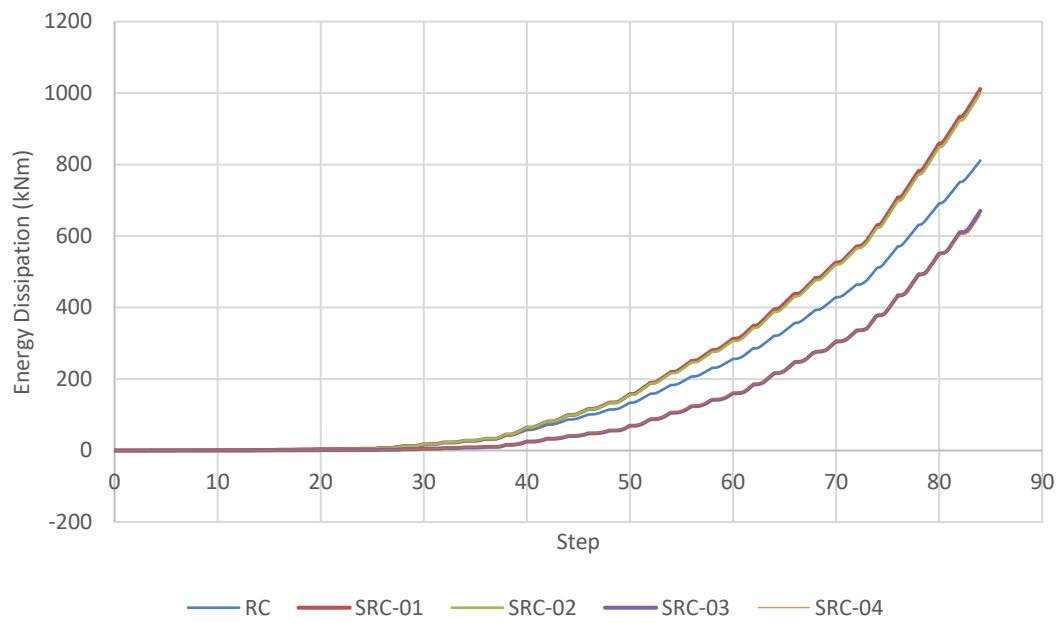
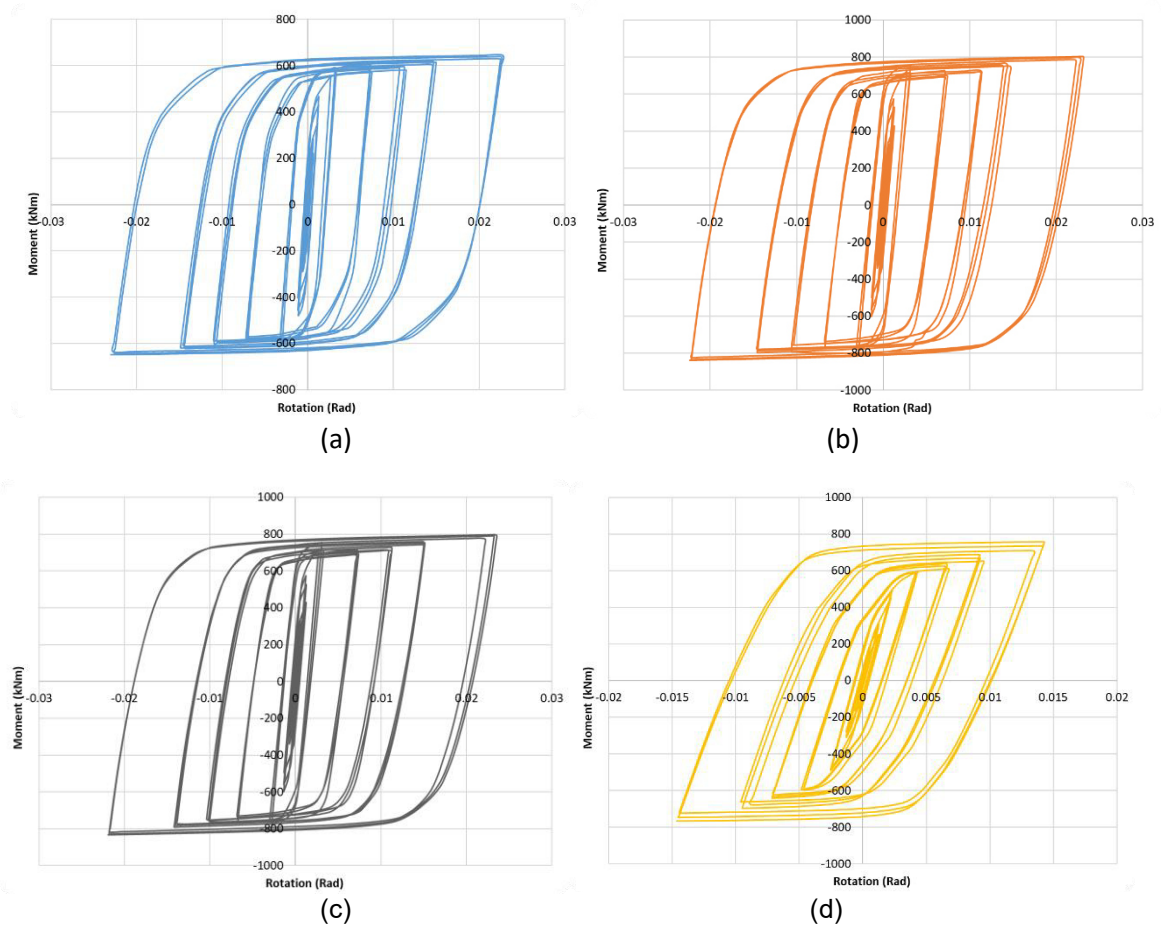
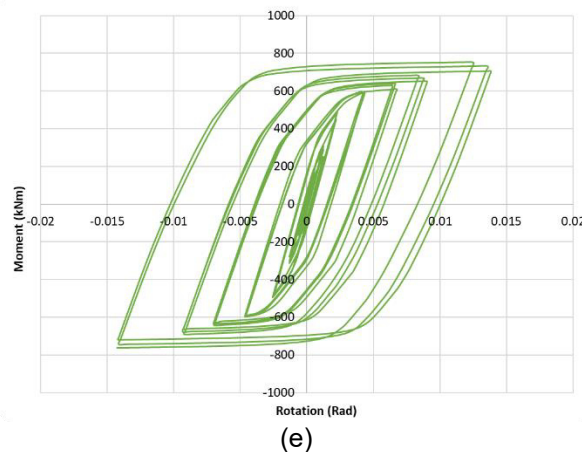


Fig. 13: Energy Dissipation Capacity

4.4 Moment-Rotation Relationship





(e)
Fig. 14: Moment-Rotation Curve of the models : (a) RC, (b) SRC-01, (c) SRC-02, (d) SRC-03, (e) SRC-04

The relationship between moment and rotation is an important parameter in evaluating the performance of beam-column joint structural elements [3]. The hysteresis curve of the beam moment-rotation is presented in Figure 14.

Table 4: Numerical Result of The Models

Model	Load Direction	Max. Moment	Max. Rotation	Max. Rotation	Comparison of Moment	Avg	Comparison of Rotation	Avg
		[kNm]	[Degree]	[Rad]				
RC	Positive	645	1.307	0.023	1.000	1.000	1.000	1.000
	Negative	-648	-1.322	-0.023	1.000		1.000	
SRC-01	Positive	805	1.331	0.023	1.248	1.270	1.018	0.995
	Negative	-837	-1.285	-0.022	1.292		0.972	
SRC-02	Positive	799	1.354	0.024	1.238	1.262	1.036	0.994
	Negative	-833	-1.260	-0.022	1.285		0.953	
SRC-03	Positive	759	0.820	0.014	1.177	1.181	0.628	0.632
	Negative	-768	-0.842	-0.015	1.186		0.637	
SRC-04	Positive	753	0.794	0.014	1.168	1.172	0.607	0.613
	Negative	-762	-0.818	-0.014	1.176		0.619	

Figure 14 is a moment-rotation curve for each model, showing that the composite beam-column joints SRC-01 – SRC-04 generate a greater moment compared to the RC models as the control model. However, in terms of beam rotation, the SRC models experience lower rotation compared to the RC model. The SRC-01 and SRC-02 models exhibit nearly the same rotation as the RC control model, while the SRC-03 and SRC-04 models experience approximately 37% lower rotation compared to the RC control model. According ACI 374.2R.13, the RC, SRC-01, and SRC-02 models meet the criteria of "Life Safety" whereas the SRC-03 and SRC-04 models meet the performance level criteria of "Immediate Occupancy".

5 Conclusions

Based on the research conducted on interior beam-column connections with SRC modifications using finite element modelling with the ABAQUS program, several results were obtained, including:

1) The failure pattern observed in several models indicates that all five models experienced failure in the beam elements facing the columns, thus achieving the seismic structure failure principle, namely strong column weak beam. However, in models SRC-01 and SRC-02, high stress is located in the outer area of the SRC beam elements, suggesting that in future research, SRC should be fully modelled on the beams.

2) Based on the load-drift ratio relationship, the initial yield of each element at a 1% drift ratio is obtained. The beam-column connection model with the highest capacity is SRC-01. Shear reinforcement indicated in the SRC area has no significant influence. As a result, it can be stated that SRC in beam-column connection elements contributes significantly to the shear force that occurs.

3) The highest energy dissipation is obtained in model SRC-01, while SRC-04 has the lowest energy dissipation capacity. Compared to the monolithic joint, the SRC-01 model has 25% higher energy dissipation capacity, SRC-02 is 23% higher, and SRC-03 and SRC-04 have 17% and 19% lower energy dissipation capacities compared to the monolithic joint (RC).

4) The composite beam-column joints SRC-01 – SRC-04 generate a greater moment compared to the RC model as the control model. However, in terms of beam rotation, the SRC models endure less rotation than the RC model.

5) Model SRC-01's beam-column connection is ideal and has high structural performance against earthquakes, as determined by various factors and results.

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